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THE

JOURNAL OF GEOLOGY

JULY-AUGUST, 1897

MORAINES OF RECESSION AND THEIR SIGNIFICANCE IN GLACIAL THEORY.[1]

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INTRODUCTION.

The principal facts which form the basis of this paper were presented in an article read before the joint session of the Geological Society of America and Section E of the American Association for the Advancement of Science at Buffalo in August 1896.[2] They may be briefly summarized as follows:

During parts of the seasons of 1893, 1895 and 1896 the writer explored the eastern coast of Michigan southward from Mackinac straits chiefly with the object of tracing the old shore lines. Incidentally, however, much information was gathered concerning the terminal moraines which lie in the same area. Their development and relations were found to be for the most part very simple. Between Mackinac straits and Toledo, Ohio, five moraines were found arranged in consecutive order or in series, and the series is regarded as complete within this interval. The work of the past season brought the moraines of Michigan into connection with those of Ohio and Indiana where their relations had been worked out by earlier observers—by G. K. Gilbert and N. H. Winchell in northwestern Ohio, by C. R. Dryer in northeastern Indiana, and by F. Leverett in western and southwestern Ohio.[1]

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[1] An abstract of this paper was read before the Geological Society of America at Washington, December 31, 1896.

[2] "Glacial Succession in Eastern Michigan." Abstract in Am. Geol. for October 1896, p. 234.

According to Mr. Leverett and Professor Chamberlin the drift of the Wisconsin glacial epoch extends down into southwestern Ohio nearly to Cincinnati.[2] Near this place its farthest limit is marked by a terminal moraine, and from this there is a series of moraines extending northward to the Maumee valley. Numbering the moraines up from the south the one that passes through Defiance is the tenth. By the work of the several observers mentioned, the whole interval from Cincinnati to the Straits of Mackinac has been explored, and the sum of the terminal moraines in the whole series is fifteen. And further, not

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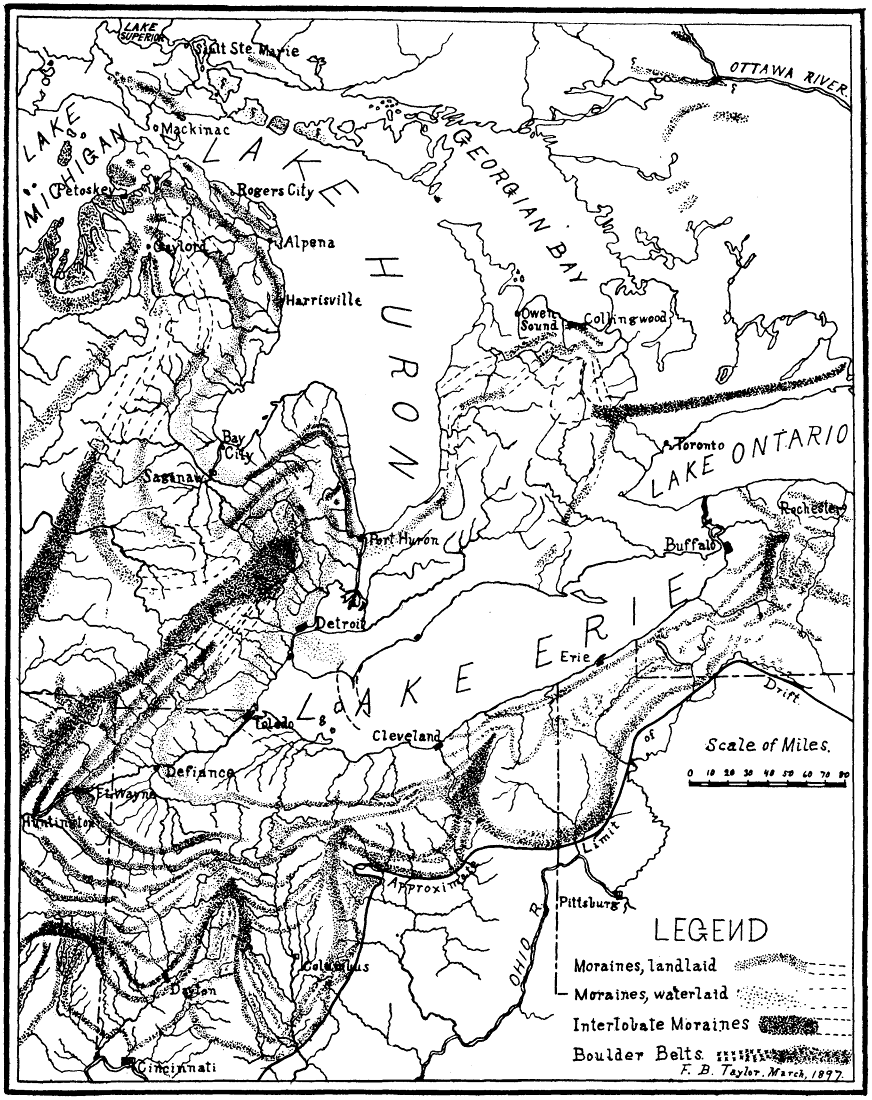
[1] GILBERT in the reports of the Geological Survey of Ohio, Vol. I, 1871, chap. xxi, p. 357. WINCHELL in Proc. A. A. A. S., Vol. XXI, 1872, pp. 171–179; Geological Survey of Ohio, Vol. II, 1874, pp. 56, 431–433. DRYER in the 16th, 17th and 18th reports of the State Geologist of Indiana, 1888 to 1894. LEVERETT in Am. Jour. Sci., Vol. XLIII, 1892, pp. 281–297; JOUR. GEOL., Vol. I, No. 2, 1893, pp. 129–146.

[2] MR. LEVERETT speaks of this as "the later drift." (JOUR. GEOL., Vol. I, No. 2, p. 138.) PROFESSOR CHAMBERLIN afterwards applied the name "East-Wisconsin formation" to this drift, and the same is now known as the "Wisconsin formation." (GEIKIE'S "Great Ice Age," 1894, p. 763 and map opposite p. 727. Also in JOUR. GEOL., Vol. III, No. 3, pp. 270 and 275.) PROFESSOR CHAMBERLIN recognizes, with a reservation of doubt, a division of the moraines of the Wisconsin formation into "earlier" and "later" groups. ("Great Ice Age," pp. 763–764.) But this division would make very little difference in the conclusions reached here. For in the Miami valley the first moraine north of Cincinnati is the only one belonging to the earlier group. All the rest of the series northward to Mackinac belong to the later group and are therefore a consecutive series in time.



Map showing Moraines of Recession between Cincinnati and Mackinac.

only is it ascertained that there are fifteen moraines between Cincinnati and Mackinac, but the conditions of glacial motion and drift deposition were so simple along the entire line that it is substantially certain that the series is full and complete. Three more moraines in the same series, but possibly not consecutive, were found north of the straits. In making the count the central axes of a connected series of wide open valleys was followed—up the Miami valley, down the Maumee, up the Detroit and St. Clair and thence northward along the west shore of Lake Huron. This course was chosen because the ice motion was naturally the freest in the open valleys where the resistance was least, and the oscillations of the ice-front were recorded there more distinctly than anywhere else. This line avoids all interlobate and other morainic complexes and follows the valley axes where the amplitude of the peripheral oscillations of the ice-sheet was naturally greatest.

On examining the configuration of the individual moraines and on comparing the intervals of distance between them (shown on the accompanying map) it is apparent that the principal irregularities of the moraine series are due to topographic influences. As the ice-sheet crept along it moved forward farthest and fastest in low wide valleys like the St. Clair-Detroit valley, and it lagged behind on the hills and highlands as on Blue Mountain south of Georgian Bay, on the highlands south of the Straits of Mackinac, and on the "thumb" between Saginaw Bay and the south arm of Lake Huron. The relative width of the valley and the relative height of the bounding highlands had a considerable effect upon the amplitude of the oscillations at any given point. For in a narrow valley, between relatively high side lands, as was probably the case to a slight extent in the Miami and Sciota valleys, the ice movement was cramped and the amplitude of oscillation more or less reduced. The ice-lobes that spread away southward from the Huron, Saginaw and Erie lake basins were wonderfully sensitive to topography. Differences of level of the general land surface over which they moved amounting to as little as a hundred or even fifty feet determined the direction of flow and shaped the lobes. The intervals between the moraines show some irregularity, but on a close study of the relief of the region, with due allowance for its influence upon the ice-motion, it seems clear that if the uneven features of the land surface had been wholly absent the moraine series would have been perfectly regular, either with equal intervals or intervals showing a regular order of variation.

VALUE OF THE CINCINNATI-MACKINAC MORAINE SERIES AS A BASIS OF INTERPRETATION.

So far as known to the writer there is no other glaciated area of like extent where a moraine series is found so simple and complete as that between Cincinnati and Mackinac. Similar moraine series are known in many other places—most notably in the adjacent areas of the Sciota Valley in Ohio, in southwestern Michigan and northwestern Indiana, and in Illinois, Iowa, Minnesota and the Dakotas, but in none of these regions are the phenomena of equal simplicity or completeness. A few moraines in series are known in the eastern states and New England, and a few also in Europe, but in all these regions they fall far short in comparison. The series of moraines extending northeastward from Defiance to Rochester, N. Y., may ultimately prove to be as good as that extending to Mackinac, but at the present time it appears to be incomplete. Eastward from Cleveland especially the lower moraines are closely packed on the steep northward slope. In the Dakota-Minnesota series Mr. Upham finds twelve moraines,[1] but it is perhaps somewhat doubtful, as was recently pointed out by Professor Todd, whether all these moraines are in one series.[2] In Illinois, western Indiana and southwestern Michigan, Mr. Leverett finds a number of moraines in series, but there are overlaps in the area, and in Illinois, especially, the individuals join and separate so often, forming a series of complex loops, that the system appears at present confused and a complete and simple series is not easily made out. The moraines of the Saginaw lobe in all probability make a simple series of at least eight or ten members, but they have not yet been fully explored. The chief element of confusion in these several areas appears to be due mainly to the influence of a relatively complex topography. There may have been other causes of complexity, but the land relief is clearly the most important.

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[1] "The Glacial Lake Agassiz," by WARREN UPHAM; Monograph XXV, U. S. Geological Survey, 1896, pp. 139–141. Also, Twenty-second Ann. Rept. Minn. Geol. Survey, Part III, 1894, p. 45.

[2] "A Revision of the Moraines of Minnesota," by J. E. TODD. Abstract in Am. Geol. for October, 1896, p. 225.

The individual moraines of the Cincinnati-Mackinac series are also as a rule simpler in their reliefs, in the curves by which they cross the valleys, and the intervals between them are wider and more regular. Their relations to each other and to the adjacent higher lands are also simpler.

On account of their completeness and simplicity, therefore, the moraines of the Cincinnati-Mackinac series constitute the best body of facts now known for the study of the cause of the oscillations of the retreating ice-sheet, and there appears to be little prospect of ever finding a better one. With few exceptions a comparison of other moraine series shows at once that the reason the Cincinnati-Mackinac series is so simple is that the land relief which the ice encountered along this line was of the simplest sort. Such a comparison in nearly every instance strengthens the conclusion that if the ice-sheet had moved over a perfectly plane surface the moraines would have been laid down at regular intervals or else at intervals varying progressively in a regular way. In short, the departure from perfect simplicity and regularity in the moraine series of any ice-lobe seems to be in a general way proportional to the magnitude, number, and complexity of arrangement of the larger topographic features which it encounters.

KNOWN PERIODIC OSCILLATIONS OF CLIMATE.

It has been supposed by many, and apparently with good reason, that northern lands were elevated to relatively high altitudes during the Ice age. This is held by some to have been the chief causal condition. But whatever the cause of the Ice age itself may have been, it seems hardly possible to account for the moraines of recession by any scheme of ups and downs of the solid earth. The moraines themselves indicate that the oscillations of the ice-front were of a periodic nature, and therefore dependent upon the operation of a periodic cause. All geological forces that are purely terrestrial are necessarily derived from the interior of the earth, and there is no evidence that their activities are periodic, although they may recur at irregular intervals. Still less is it possible to conceive of true periodicity in the surface manifestations of purely terrestrial forces, such, for instance, as would be required to explain periodic movements of elevation and subsidence over wide areas, especially where the amount of the successive movements would have to be regulated to the extreme nicety of progressive variation requisite to produce the climatic cause of the moraines of recession. All such supposable terrestrial causes may therefore be safely put aside.

To find a source for periodic causes we are compelled to turn to astronomy. According to established doctrines the only way in which astronomical forces can be supposed to influence glaciation is through climate. The annual period of climatic change is so short that it is, of course, out of the question. A period of climatic change in rounds of about thirty-five years has been deduced by Forel and others from the study of the variations of glaciers and of rainfall.[1] But, as will be shown farther on, this too seems far too short. After this the only known period of climatic variation is that due to the precession of the equinoxes, and the movement of the perihelion of the earth's orbit. Mr. G. K. Gilbert has used this period of climatic oscillation in connection with another matter. His statement relating to the length and variability of the precessional period is concise and convenient. "The precessional period is about 26,000 years, but the position of the perihelion also moves — for the most part in a direction opposite to that of the equinoxes — and the resultant of the two motions has an average period of about 21,000 years. It is not absolutely regular, but ranges ordinarily within 10 per cent. of its mean value, and exceptionally to 50 per cent. above and below."[1] The period at 21,000 years seems too long, but if we take it at its minimum of 10,500 years, it may not be.[2]

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[1] F.-A. FOREL. (Archives. Sci. Phys. Nat., May 15, 1886, p. 503.) Forel points out that the variations of rainfall and air temperature, as deduced by C. Lang, agree with his own periods of variation in Alpine glaciers. (Also Am. Jour. Sci., for July 1886, p. 77.) In Forel's latest writing on this subject ("Les Variations Periodiques des Glaciers," Genève, 1895) he finds the grounds for deducing a definite period to be rather unsatisfactory. He finds that glaciers of different sizes and lengths do not show the effects of causes of advance or retreat synchronously. After a few seasons of increased precipitation all glaciers tend to advance, but small ones advance sooner than great ones so that they do not attain their maxima at the same time. A small glacier will reach its maximum and get far back on its retreat before a greater glacier attains its maximum advance — a result that is natural from the fact that the effects

THE THEORETICAL EFFECT OF PRECESSIONAL OSCILLATIONS OF CLIMATE UPON THE ICE-SHEET.

Let us see in what manner the astronomical forces would work, supposing the oscillation of the ice-front to be due to precession. Precession is produced by the rotation of the axis or pole of the earth around the pole of the ecliptic. The figure thus described on the celestial sphere is not in reality a true circle, but for the purposes of this paper it may be assumed that it is, without in any way impairing the general truth or validity of the conclusions reached. The general idea of the influence of precession upon terrestrial climate has been so often discussed that it is hardly necessary to dwell at length upon it here. But it is

of causes of advance or retreat proceed in waves downward from the névé to the end of the ice-tongue. From this and other causes of complication he finds it hard to make out clearly any regular period of variation. Nevertheless, it is probable that a thirty-five-year period exists. The progress of investigation along this line is well summarized by Professor H. F. Reid, "Variations of Glaciers," JOUR. GEOL., Vol. III, No. 3, 1895, p. 278 et seq.

[1] "Sedimentary Measurement of Cretaceous Time," by G. K. GILBERT. JOUR. GEOL., Vol. III, No. 2, 1895, pp. 121–127.

[2] There is a possibility that the period of precession during the glacial epoch was considerably shorter than the minimum of the modern calculation. Perhaps the chance of this seems very remote, but there are small changes going on, now apparently secular, which in so great a lapse of time may prove to be periodic and may come to be of prime importance in their effects on terrestrial climate.

necessary to see clearly how the position or place of the ice-front is related to this kind of climatic change. The change of climate from this cause does not go on with the rotation of the earth's pole *pari passu.* For the pole, under the simplified conditions here postulated, moves in a circle and changes its position at a uniform rate. The effect of this movement on climate is to produce a periodic or oscillatory change to and fro between two extremes or climaxes, and these changes go on in an endless alternating series, from cold to warm, from warm to cold, from cold to warm, and so on. In glacial times a climatic variation of this sort, even if it were slight in amount, must have had its effect on the ice-sheet. As climate grew more severe the ice-sheet would advance its front all along and spread over a larger area, and as climate moderated the ice-front would draw back and the area of the ice-sheet would be reduced. Thus it may be demonstrated that the effect of a precessional oscillation of climate upon the ice-sheet would be to cause it to alternately increase and decrease its area by a series of expansions and contractions, and this process would necessarily be accompanied by a corresponding series of alternate advances and retreats of the ice-front. We are thus enabled to infer the character or manner of the oscillations of the ice-front, supposing them to be due to precession. They would obviously follow the manner of what is called simple harmonic motion. If a wheel be made to rotate on a fixed vertical axis a point or peg on its rim describes a circle when viewed from above. But if we look at the wheel edgewise, or from the side, the peg appears to move to and fro along a straight line, more slowly near the ends, fastest in the middle, and coming to rest for an instant at each extremity. The manner of the apparent motion is like the swinging of a pendulum viewed from below. This is the manner in which the forward and backward movements of the ice-front would take place if produced by precession. As the cold increased after a warm climax, the ice-front would advance, at first slowly, but at increasing rate, until the middle point of the oscillation was reached; then more and more slowly until it came to rest at its cold or forward climax, where it would halt and build a terminal moraine. Then as climate ameliorated the ice-front would retreat in the same fashion and at its warm or backward climax it would again halt and build a moraine. The moraines of the cold climaxes would always be built after an advance movement, and would therefore be left standing. But the moraines of the warm climaxes would always be built after retreats and just before advances, and would therefore be overridden and destroyed. From these considerations it is plain that the time during which the ice-front would stand at or near its extreme forward position while building its terminal moraine at the cold climax would be only a fraction of the whole precessional period. The precise value of this fraction depends upon three factors: (1) on the period or duration of the precessional oscillation of climate; (2) on the amplitude of the oscillation of the ice-front, and (3) on the width of the drift belt which takes the form of a terminal moraine at the cold climax. The character of the moraine built would vary considerably according to the manner of combination of long or short periods with small or great amplitudes. Other factors, such as the quality and quantity of the drift, the land relief, the situation with reference to the margin of the lobe (frontal or interlobate), latitude and local climatic influences modify the character of the moraines more or less, but need not be discussed further here.

By way of illustration let us consider a hypothetical case Suppose the amplitude of oscillation to be thirty miles, which is probably not far wrong for certain localities, and the period to be 10,000 years, which is in round numbers the supposed minimum value of the precessional period. The moraines are from two to ten miles wide, the average being not far from five. Their width varies considerably in different regions and different situations, but the figures given are approximately true for northwestern Ohio, northeastern Indiana, and southeastern Michigan

Figure 1 represents a simple harmonic motion in which *A B C D* is the circle of reference and represents the circle which the pole of the earth describes on the celestial sphere in 10,000 years. The diameter *A C* may be taken to represent the amplitude of the oscillation of the ice-front as affected by the precessional oscillation of climate, and is put at thirty miles. Of course the ice keeps melting as it moves forward so that there is no material thing that constantly accompanies the ice-front as it changes its position. But we may imagine a point which shall keep its place constantly at the front edge. This point would move to and fro with the ice-front on the line *A C*, following the order of the precessional changes of climate. An arrow within the circle shows the direction of the general glacial flow, which is maintained in the glacier itself through all phases of advance and retreat of the ice-front. The climaxes of cold will therefore be at *A* and the climaxes of warmth at *C*, and the ice-front will have a period of rest at each of these points. When the ice-front passes *O* it will always be moving at the maximum rate, whether of advance or retreat. As the ice-front moved forward from *O* to *A* its rate of advance would decrease, and would become very slow on approaching near to *A*, and the retreat

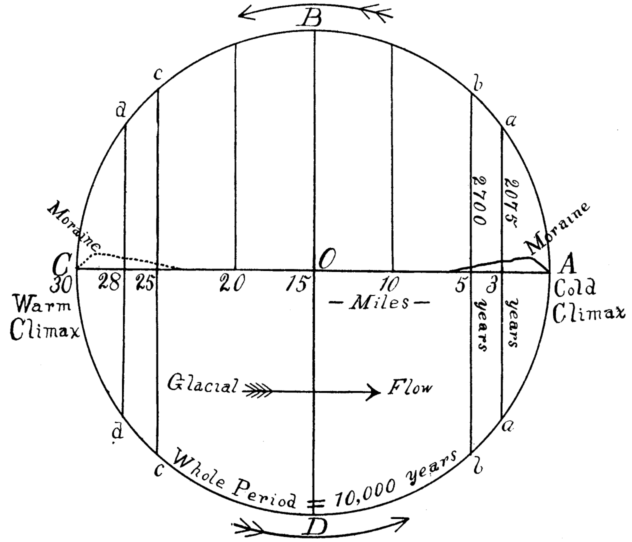

FIG. 1.

from *A* to *O* would have the same character in reverse order. The five miles nearest to *A* represents the approximate width of the belt in which terminal moraines at the cold climaxes are built. If the whole period of precession be 10,000 years and the amplitude thirty miles, it is easy to show that the ice-front would be within the five-mile belt (*bb'*) about 2700 years, and within the three-mile belt (*aa'*) about 2075 years. A period of terminal moraine building of the same duration would also take place at *C*, the warm end of the oscillation, but the moraines built there would always be overrun and destroyed at the next advance.

If this process were carried on with ideal simplicity the resulting forms of the terminal moraines at the two extremes of oscillation would be substantially as represented in cross section in the figure. Those at *A* would have relatively short, steep front slopes and long, gentle back slopes, while those at *C* would have long, gentle front slopes and short, steep back slopes. In the moraine series as we have it, all those made at *C* have been destroyed, and we have left only those made at *A*. We shall see presently that where the conditions were simplest the moraines do in fact show plainly a tendency to take the form shown at *A*.

If the period of precession were 20,000 years, the amplitude remaining the same, the time of the ice-front in the five-mile belt would be doubled, or 5400 years. On the other hand, if the period were 5000 years the time in the five-mile moraine belt would be 1350 years, and in the three-mile belt 1037 years.

The character of the moraine would also be affected by the amplitude of the oscillation, the period remaining the same. The amplitude would necessarily vary greatly in different places, the chief determining condition being the character of the land relief and the relation of the ice to it. Against a steep slope towards the ice the oscillation would be greatly reduced and the moraines would be closely packed together, as is seen in interlobate areas. In wide flat areas, like the Saint Clair-Detroit and Maumee valleys, the amplitude would be at its greatest.

The general application of this idea to the oscillations that took place is plain on a comparison of the course of any two contiguous moraines of the series from their apexes in the center of the valley to their turning point in the interlobate. The Fort Wayne and Defiance moraines are nearly fifty miles apart at their apexes, but they converge as they rise toward the northeast until they are only eight or ten miles apart a few miles beyond Adrian. On this basis it would be expected, further, that the moraines themselves would be comparatively wide and flat where the amplitude of oscillation was great and *vice versa* Here again there is some evidence of agreement of fact with theory. With the period of oscillation at 10,000 years and the amplitude at 100 miles, which appears to have been its approximate measure after passing Fort Wayne, the five-mile moraine belt would be occupied by the ice-front about 1345 years, and a ten-mile belt about 1920 years.

THE CHARACTER OF THE GLACIAL OSCILLATIONS AS REVEALED BY THE DRIFT.

Assuming that the moraine series was produced by a climate oscillation it becomes a matter of the highest importance to discover if possible what the character of that oscillation was Did the ice-front merely retreat and halt in the simplest possible rhythmic fashion, or did it follow a more complicated movement of alternate retreats and readvances with halts between? It would be expected that the way in which it was built would make some difference in the form or shape of a moraine. If the moraines took any dominant or common form, and if that shape corresponded to one that would result theoretically from some particular process, it would be fair to presume that that had been the method of their building.

At a first glance it would appear that the moraines show no recurrent features that are particularly suggestive in this respect, and it must be admitted that many of them, perhaps the majority, do not. At least they do not show such features clearly enough to be readily recognized. But there are some of the moraines that do show a marked tendency to take a particular form, and it is upon these that we must rely.

Here again it is necessary to recur to the law of the higher value of the simplest phenomena as a basis of interpretation when compared with those that are more complex. If in the present state of our knowledge we go to the compounded moraines of interlobate areas, or to the more or less obscure moraines of the mountains or hilly eastern states, it will be found very difficult to reach any satisfactory conclusion. But some of the moraines of northern Indiana, northwestern Ohio, and southeastern Michigan present the utmost simplicity of form, and were built under the operation of forces acting in the freest and simplest way possible. Upon these moraines, and especially upon those of them that seem to be most typical in their simplicity, I rely mainly for the conclusions reached.

The moraines of northeastern Indiana have been studied in detail by Professor C. R. Dryer, from whose report I quote as follows:

> The peculiar topography of the Wabash-Erie region in Indiana would be strikingly shown by a section along any line radiating southwesterly or northwesterly from Paulding, Ohio. Such a line would run nearly level across the Maumee Lake bottom to the Van Wert and Hicksville Ridge, then rise 80 to 100 feet in four or five miles to the crest of the St. Marys and St. Joseph moraine, then fall fifty feet in about one mile, then cross a level interval of from one to ten miles, then show a second gradual rise and more abrupt fall, across the Wabash-Aboite moraine, and the second terrace averaging about sixty feet higher than the first. In the southern portion two more terraces lie beyond the Wabash Ridge.[1]

[1] Sixteenth Ann. Report of Indiana State Geologist, 1888, p. 123.

My attention was first called to the remarkable series of terminal moraines in northeastern Indiana and northwestern Ohio by the work of Professor Charles R. Dryer in the summer of 1886. As assistant to the state geologist, Professor Dryer was at that time making a survey of the northeastern counties of Indiana. Some acquaintance with the features of eastern Indiana southward as far as southern Randolph county and also with the region around Saginaw Bay in Michigan led me to extend the series provisionally, recognizing its probable incompleteness, to those regions. The idea that these moraines might mark precessional variations of climate was adopted by me then as a tentative hypothesis. The drift of opinion since then among American geologists, however, has been largely against anything like so

This is distinctly the character that should be expected in moraines built at a climax of advance in which the advance, the halt and the subsequent retreat take place after the manner of the cold climax of an oscillation like that shown at *A* in Fig. 1 above. The crest of the ridge is toward the front edge, the back slope is long and gentle, while the front slope is shorter and steeper. This type of moraine is well illustrated in cross section by the profile of the Wabash Railway as it passes over the Defiance moraine east of that place. This is shown in Fig. 2.

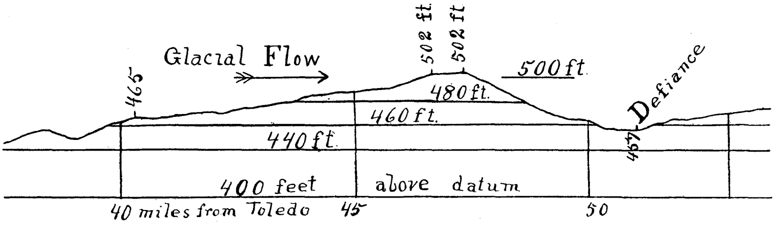

FIG. 2. Profile of Defiance Moraine.

As shown on this profile the crest of the moraine rises above

liberal an allowance of time for the glacial retreat as this hypothesis would seem to require. Moreover the moraine series remained fragmentary and incomplete until a year or so ago, so that there was not a sufficient foundation of fact to warrant the presentation of the idea. Nor had the remarkable Greenland explorations of Chamberlin, Salisbury, and others furnished the present strong foundation for the idea of slow motion of ice-sheets and slow transportation and deposition of drift. Without adopting the idea of precession as a cause, Professor Dryer fully recognized the general significance of the moraines, as the following words from his report show. After speaking of the possibility that each moraine marks the culmination of a separate glacial epoch, he says: "It seems more probable, however, that they are moraines of recession and mark halting places in the retreat of one and the same ice lobe. When their uniformity of mass, strict parallelism and occurrence at regular intervals are taken into account, the whole arrangement will perhaps prove to be unique among the glacial phenomena of North America. Their greatest importance lies in the evidence which they afford of regular periodical oscillations of climate. The outer edge of the ice lobe occupied a certain position long enough to form a moraine five miles wide and 100 feet high; it then fell back fifteen miles and occupied another line long enough to form a similar moraine. These alternating halts and retreats were repeated four or five times, the last retreat being thirty [fifty ?] miles, and the last moraine, the Blanchard Ridge of Winchell, being smaller and less symmetrical" (p. 124).

its base somewhat more than forty feet, but the real crest is somewhat higher than the railroad track. The front or western slope is about two and a half miles long and the eastern or back slope about seven miles. It has been suggested that the moraines that show this form owe their steeper front slopes to the action of marginal glacial rivers which have carried off the deposit on that side. No doubt there was a slight influence of this kind in some cases, but there certainly was none in the case of the Defiance moraine, for it was laid down in about sixty feet of still water (glacial Lake Maumee) and there was no chance for a stream to act until the ice-front had retreated beyond Detroit nearly to Port Huron. While the Leipsic beach was being made the water still stood about thirty feet deep at Defiance, and it was only when it fell to the level of Lake Whittlesey (Belmore beach) that marginal rivers began to exist. The depression shown at Defiance in the profile is the bed of the Maumee River which began to flow at the same time. But the Maumee is a much larger stream than Tiffin or Bean Creek that comes in from the north along the moraine front, or the Auglaise River, which comes in from the south in the same relation. Formed under such circumstances it is obvious that the Defiance moraine was originally shaped in the building as we find it now, and does not owe its form to the action of a border river. Part of the Saginaw moraine, between Ubly and Cass City was probably steepened by the large rapid outlet river which flowed along its front, but apparently none of the other moraines of this type were notably affected in this way. The rest of the Saginaw moraine is a fine specimen of the type here referred to.[1]

This character of the moraines, however, is not confined to the particular tri-state area mentioned above. The same general type is only a little less distinctly developed in several other places, and is recognized by other observers. Mr. Leverett, speaking of the glacial drift of the northeastern third of Illinois, says:

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[1] Some account of Lake Whittlesey and the Saginaw and Port Huron moraines with brief mention also of the Toledo and Detroit moraines may be found in "Correlation of Erie-Huron Beaches with Outlets and Moraines in Southeastern Michigan," Bull. G. S. A., Vol. VIII, 1897, pp. 31–58. Also "Glacial Succession in Eastern Michigan," abstract in Am. Geol., Oct. 1896, p. 234.

> In the portion of the state covered by the newer drift there is a succession of morainic ridges formed by the ice-sheet during its retreat from the Shelbyville moraine. These ridges are separated by drift plains or basins from a mile or two up to thirty or forty miles in width. These plains usually show a gradual rise on their landward (west and south) borders, while on the iceward borders (toward the Lake Michigan basin) they are found to rise abruptly to a moraine. The streams which now drain this region naturally choose the axes of these basins for their main channels while the slopes carry the tributaries. It is the long slopes on the west and south, and the short slopes on the opposite side which have caused the tributaries of the streams to be mainly from the west and south.[1]

It will be noted that Mr. Leverett speaks of the slopes of the plains rather than of the moraines. Each moraine, however, may be regarded in some sense as the projecting upward edge of the gently inclined plain that merges with its back slope. Professor Todd notes this relation in his description of the moraines of Dakota where he says:

> It is assumed that the reader is familiar with the generally recognized features of drift formations, such as the undulating topography and the series of drift deposits, covering an area with successive layers of till in a manner which might be compared to a nest of spoons of assorted sizes, the smaller lying inside the larger. Of these spoon-shaped deposits, the moraines form the outer rims.[2]

It is very gratifying to be able to add to the weight of the foregoing opinions that of Professor Chamberlin, whose study of glacial problems has been close and prolonged, and whose experience in observation is probably wider than that of any other one man. It is hardly less than remarkable that his views of the glacial retreat should accord so closely with the requirements of the hypothesis here presented.

But so far as known to the writer this manner of glacial retreat has not been associated by Professor Chamberlin with the causes here suggested. According to his view the drift of each main ice invasion was laid down in imbricate fashion; that is, there was a continual oscillation with moderate readvances as the general retreat progressed, so that the drift was laid down in successive overlapping sheets somewhat like the weatherboards on a frame house, or the shingle rows on a roof. In Geikie's *Great Ice Age*, under "The Imbrication of the Drift Series,' beginning on page 736, his views are given as follows:

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[1] "The Water Resources of Illinois," by FRANK LEVERETT. Extract from 17th Ann. Rep. U. S. Geol. Surv., 1895–6, p. 13. Also in "Pleistocene Features and Deposits of the Chicago Area," Chicago Academy of Science, Bull. No. II, May 1897 p. 17.

[2] "The Moraines of the Missouri Coteau and their Attendant Deposits," by JAMES E. TODD, Bull. U. S. Geol. Sur. No. 144, 1896, p. 11.

> The drift deposits of the great plain region of North America may be looked upon as a series of sheets overlapping each other in imbricate fashion; the outermost disappearing beneath the next inner, and this, in turn, dipping beneath the succeeding, and so on. The outer uncovered zone of each sheet retains its original form, except as modified by superficial agencies, but the inner buried zone was much modified by the over-riding ice during the later advances. In a general view of the drift, it is important to grasp clearly this conception of the overlapping of the sheets, and to distinguish this imbricate structure from the simple stratigraphical superposition of marine sediments on the one hand, and of simple morainic corrugations following each other in concentric recessional lines on the other. It is, furthermore, important to observe that this is only a superficial conception of the drift series. Theoretically, there are at least two of these imbricate series for every period of glaciation, and the order of imbrication takes on opposite phases. During the first part of the glaciation, when the ice on the whole was extending, though by alternate advances and retreats, the later were generally greater than the earlier advances. During the succeeding stage, however, when the ice was, on the whole, retiring (though by oscillations) the later advances generally fell short of the earlier. In the case of the lower or older series of glacial accumulations, therefore, the later deposits generally reach farther south than the earlier ones, whereas, during the recessional stages of glaciation, the earlier sheets extend farther south than the later. These two imbricate series of sheets of contrasted order represent the two great halves of a period of glaciation. If there were two or more entirely distinct periods of glaciation theoretically the double imbricate series repeated itself accordingly. . . .

There is one other class of facts that may ultimately be added to the proof of readvances in the oscillations. Bowlder belts, at least in certain situations, are believed to indicate readvances. Respecting the source of the bowlders themselves it seems safe to say that ninety-nine out of every one hundred in western Ohio, in Indiana, and Illinois are of Canadian origin, and nearly all are of the hardest crystalline varieties. Considering the dominant englacial mode of transportation, the continual and very complicated changes in the direction of glacial flow and the dispersion from the lobate axes, it becomes extremely difficult, if not altogether impossible, to account for the bowlder belts except by the intervention of some later agency of bowlder concentration—some agency that operated near where the bowlder belts are now found. It seems impossible that any marked bowlder belt could have been brought all the way from Canada with the bowlders in such close relationship as that in which they now lie. Some of the bowlder belts of southwestern Ohio, southeastern and western Indiana are very pronounced in their development. It is conceivable that they might have been formed by the marginal concentration of superglacial or englacial bowlder trains, but it is hard to think of those trains as coming directly all the way from Canada.[1] The distribution of bowlder belts is peculiar and indicates that the conditions of their production are exceptional. One moraine may show a well-formed bowlder belt, while its neighbors parallel with it in front and behind have none. The diverse composition of the bowlders seems also to be against the idea of concentrated bowlder trains. In short, it would seem that we must look much nearer than Canada for the cause of their very local concentration. The only local cause that seems available grows out of the relation of the readvancing ice-front to powerful lines of drainage at or near the edge of the ice. If, during the building of a terminal moraine, a powerful stream of water sweeps past the front of the ice so as to carry away the finer material the bowlders may be left on the surface in greater numbers than usual. Several of the well-known abandoned outlets have more or less of this appearance. But where this is the whole process the bowlders remain in a low position with respect to the surrounding lands. If, however, a readvance of the ice takes place the bowlders in the channel may be gathered up and transported some distance and finally be deposited on or in a rugged hilly moraine even to its topmost parts. In being carried forward the bowlders may be more or less dispersed, or they may be concentrated, or neither of these effects may appear. In each case it depends mainly upon the relation of the river channel to the direction of ice-motion. If the channel were straight and also normal to the ice-front the readvancing ice would carry the bowlders all forward down the channel and concentrate them in a pile where it stopped. If the channel lay athwart a pointed ice-tongue and close in front of it, the readvance would disperse the bowlders somewhat. There is a bowlder belt in Whitley and Huntington counties, Indiana, which may be due to partial concentration by a readvance diagonally across the bed of a great river corresponding to the stream that

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[1] "Bowlder Belts Distinguished from Bowlder Trains—their Origin and Significance," by T. C. CHAMBERLIN. Bull. G. S. A., Vol. I, 1890, pp. 27–31.

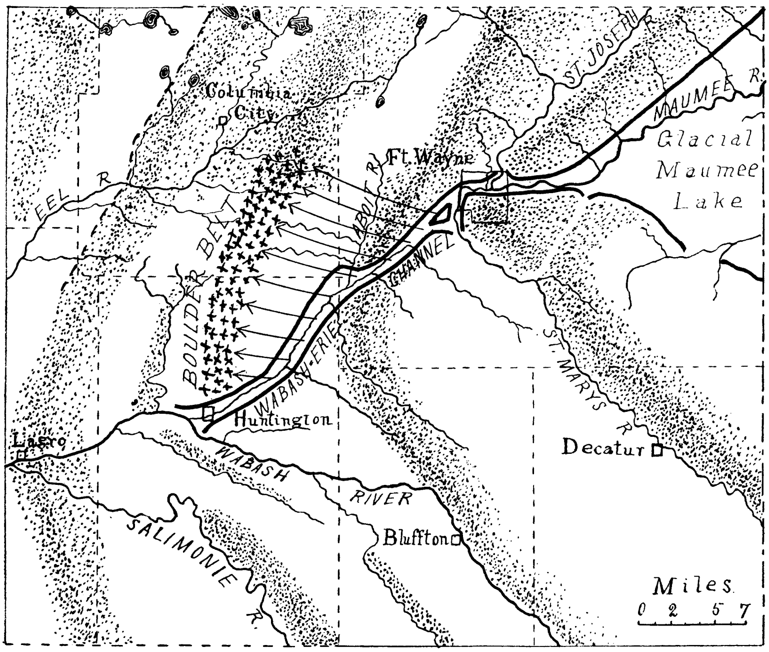

FIG. 3. Showing relation of the Whitley bowlder belt to the Wabash-Erie channel.

afterwards existed as the outlet of the glacial Maumee lake. The accompanying sketch map shows the relation. Dryer and Leverett show this belt on their maps.[1]

The disposition of this belt seems to show that the ice-front had retreated at least to Fort Wayne from the moraine next west of the bowlder belt in Whitley county, and halted while the large river excavated a channel about where the present old outlet bed is between Fort Wayne and Huntington. Then by a readvance the bowlders which had been left in this bed were carried forward by the ice, which moved in a direction normal to the ice-front, but diagonally across the river bed, and deposited them in the Whitley morainic bowlder belt. If this took place, then it is plain that the ice-front had retreated to Fort Wayne and that it readvanced over more than half the space it had just uncovered at the preceding retreat which was, therefore, not less than thirty miles.[2]

This interpretation of the Whitley belt is not yet a sure inference, for further and more particular investigation will be required to fully verify or disprove it. The Montgomery-Benton county belts seem to be somewhat similarly related to a readvance over a part of the Wabash River bed, and possibly to a former river bed about where Wild Cat Creek is now, and the Iroquois belt may have had a similar relation to the Tippecanoe River or to a glacial river that crossed from the Kankakee to the Wabash farther west, but was obliterated by the readvance.

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[1] DRYER in 18th Report of Indiana State Geologist, 1894, p. 84. LEVERETT in the "Inland Educator" (Terre Haute, Ind.), for August 1896, opposite p. 24. DRYER shows only that part of the bowlder belt which lies in Whitley county; LEVERETT shows it extending on southward nearly to Huntington. The accompanying sketch is compiled from their maps.

[2] The range or amplitude of oscillation may have been considerably more than thirty miles. Indeed, after the ice-front left Fort Wayne it must have been greater, for the four intervals from this place to Port Huron are almost exactly fifty miles each. The amplitude of oscillation was probably twice this or a little more — 100 miles or over — if the Whitley bowlder belt can be relied upon to indicate a readvance from Fort Wayne. The probable cause of the difference in amplitude east and west of Fort Wayne will be discussed later on.

On the whole, the character of the oscillation as one that was always accompanied by a readvance after recession seems to be well established by several different lines of evidence and by several of the most experienced observers.

THE PROBABLE RATE OF ICE-SHEET MOTION.

The great ice-cap of Greenland bears a closer analogy to our own Pleistocene ice-sheet than any other ice mass yet studied. The observations of Peary, Chamberlin, Salisbury, and others throw no uncertain light on the problems of ice-sheet motion as there exhibited. On this point Professor Chamberlin says:

> Lieutenant Peary has commenced a series of observations upon the movements of glaciers of the Inglefield Gulf region, both by instruments and by photographs taken at intervals. He found the daily movement of the Bowdoin glacier, the most active in the immediate vicinity of his headquarters, during the month of July to be four-tenths of a foot at the slowest point, and 2.78 feet at the fastest point, near the center, with an average of 1.89 for the whole.[1]
>
> The movement of the majority of the glaciers in that region is very much slower; indeed, in most cases it is obviously exceedingly slow. Many of the ordinary signs of movement are absent. In front of the Fan glacier there are cones of granular ice brought down by the surface streams, and also embankments of old snow, soiled, granulated, and half solidified into ice, as though at least a year old, all of which lie banked against the terminal face of the glacier without any indication of movement on its part since their formation. As these lean against the face to heights of thirty or forty feet at least, it is obvious that there had been no melting of the base of the extremity to counteract the effects of advance. Phenomena of similar import were observed in several other glaciers. The very firm impression was given by such physical signs that the average rate of movement of the glaciers of the region is very slow. At the head of the gulf are a few glaciers which produce large icebergs and which must be notable exceptions to the prevailing slowness of motion.[2]

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[1] According to Professor Chamberlin (JOUR. GEOL., Vol. V, No. 3, 1897, pp. 229–232), the Bowdoin glacier is six or eight miles long, about two miles wide in its lower part and descends between 2000 and 3000 feet. After its separation from the ice-cap by a somewhat steep fall, the Bowdoin glacier becomes essentially Alpine in type. Hence it does not furnish a criterion that can be applied to the ice-cap itself. Slow as is the advance of the Bowdoin glacier, it is probably much faster than that of the edge of the main ice-cap.

[2] Recent Studies in Greenland, Bull. G. S. A., Vol. VI, 1895, pp. 216–217.

Again, discussing glacial motion more broadly, Professor Chamberlin says, referring to Greenland:

> No average measurements, nor anything approaching to average measurements, have been made. The high rates of movement of the Jacobshaven glacier, as given by Helland, and of the Great Karajak glacier, as given by Drygalski, and other similar measurements, are not at all questioned, but these are quite exceptional, and almost as far as possible from being representative. They exhibit extraordinary movements through deep constricted straits, where the ice is forced by the vast accumulations of great areas in the rear, and where the warm season appears to exert its earliest and greatest effects. The amount of ice discharged in the form of bergs from these two glaciers is very much greater than from any other known points on the ice-front of Greenland. It is perfectly obvious that the average border of the Greenland ice-sheet does not move at a rate even distantly approximating that of these two straits. If it did so, the whole coast of Greenland must be overwhelmed almost immediately, because the competency of the summer heat of that region to hold back the edge of the ice by melting is very slight. Drygalski estimated the annual surface melting at seven feet. Even this is much greater than the annual surface melting of the Inglefield Gulf region, judged by that of 1894. While estimates are few, and even these may need much qualification, it is nevertheless certain that the average movement of that portion of the border of the Greenland ice-cap which lies upon the land is extremely small. Of that portion which ends in the sea only a small fraction has a high rate of motion, as is shown by the lack of activity in the discharge of icebergs. When it is considered that the land border is very much greater than the sea border, and that of the sea border a portion has a relatively slow movement, it will be evident that the average rate of movement for the border of the great ice-sheet of Greenland cannot be high; and the average rate of this border is the nearest available analogue to the border movement of the still more extended periphery of the ancient American or Laurentide glacier.[1]

There can hardly be a doubt of the great value of the Greenland observations in their bearing on the conditions attending the Laurentide glacier that invaded the United States. It will be observed that most of the measured rates of motion reported by Peary, Chamberlin, and Salisbury are of ice tongues flowing out a few miles from the main cap down valleys generally steep. None of the measurements are of a broad lobate front such as any one of our great lobes presented south of the lake basins. One would expect the rate of motion to be still slower where it was evenly distributed along a broad front.

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[1] The Glacial Lake Agassiz, by WARREN UPHAM. Monograph XXV, U. S. Geol. Survey, 1896. Topic entitled "Alternative Interpretations," by T. C. CHAMBERLIN, pp. 248–249.

There is another character of the borders of the Greenland ice that is a valuable aid in interpreting rates of motion. In all glaciers that move at a relatively rapid rate, as is the case with most Alpine, and fiord, or berg-producing tongues, the ice is cracked and broken deeply, and shows a rough, tempestuous surface with crevasses more or less numerous and deep. Slowly moving glaciers do not show much of this character, but are comparatively solid and smooth down to their ends, and this is the character of nearly all the glaciers that end on land as described and shown in photographic illustrations by Chamberlin and Salisbury.[1]

There is a circumstance connected with some of the moraines in the Cincinnati-Mackinac series which seems to leave little doubt of the slow motion in the great ice-lobes that made them. According to Professor Dryer the front of the Erie ice-lobe at Defiance, Ohio, stood in about sixty feet of water, that being the deepest point of Maumee Lake. But since the recent recognition of the low, faint, water-laid moraines it is found that the front of the ice halted successively at Toledo, Detroit, and Port Huron, in each case standing in about 200 feet of water. The points mentioned mark the apex of the lobe at each halt, and the place of the water-laid moraines and their land-laid extensions seem to show that the ice fitted itself to the valley relief in each case almost as perfectly as it would have done if the water had not been present. This fact throws much valuable light on the condition of the ice when it stood in these positions. Baldwin, Upham, and others have supposed from certain evidence they have adduced that lobes ending in glacial lakes broke up like calving fiord tongues and floated away so rapidly as to make their fronts concave.[1] Chamberlin seems to show this effect by two moraines in the basin of Lake Agassiz on his map in Geikie's *Great Ice Age*, 1894 (opposite page 727). Whatever the facts may be for the Lake Agassiz basin, this was certainly not the case with the Huron-Erie lobe. The fact that the ice was able to keep its place in 200 feet of water almost as though no water were present shows (1) that it was not broken and deeply crevassed into loose blocks that might easily float away, but was comparatively solid and compact, proving (2) that its motion must have been of the slow order rather than of the rapid; (3) that its thickness at the edge as it then existed must have been considerably more than 200 feet, probably not less than 300 or 400 feet; (4) that although the front must have been undercut and broken off to some extent by wave action, flotation, and melting in the lake water, this process did not become a factor of sufficient importance to seriously disturb the line of the ice-front as determined by land relief alone. The Saginaw lobe shows the same ability to conform to the land relief while standing in water at the Saginaw moraine over 150 feet deep.[2] I am led to believe, therefore, tentatively, that the motion of the ice-sheet while building the moraines of recession was very slow. That is, it was so slow that the lobes as they crept along remained essentially solid to their extreme edges.

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[1] Glacial Studies in Greenland, by T. C. CHAMBERLIN, JOUR. GEOL., Vol. II, Nos. 7 and 8, 1894; Vol. III, Nos. 1, 2, 4, 5, 6, and 7, 1895; Vol. IV, No. 5, 1896. Recent Glacial Studies in Greenland, Bull. G. S. A., Vol. VI, 1895.

The Greenland Expedition of 1895, by R. D. SALISBURY, JOUR. GEOL., Vol. III, No. 8, 1895; Salient Points Concerning the Glacial Geology of North Greenland, JOUR. GEOL., Vol. IV, No. 7, 1896.

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[1] Glacial Lake Agassiz, Monograph, by WARREN UPHAM, Plates XVII and XIX. Pleistocene History of the Champlain Valley, by S. P. BALDWIN, Am. Geol., Vol. XIII March 1894, p. 181.

[2] Nansen, in his "Farthest North," Vol. II, p. 339, describes a glacier-front of this kind in Franz Josef Land in the following terms: "We were soon underneath the glacier, and had to lower our sail and paddle westward along the wall of ice, which was from fifty to sixty feet in height, and on which a landing was impossible. It seemed as if there must be little movement in this glacier; the water had eaten its way deep underneath it at the foot, and there was no noise of falling fragments or the cracking of crevasses to be heard, as there generally is with large glaciers. It was also quite even on the top, and no crevasses were to be seen. Up the entire height of the wall there was stratification, which was unusually marked."

There are some writers who make the whole period of glaciation very short. Mr. Upham believes that Lake Agassiz "endured only a thousand years or less," and he allows "only a few (perhaps four or five) thousand years" for the entire glacial retreat, including the whole Champlain period of submergence and most of the later reëlevation of the land.[1] But it seems to me that both fact and theory as they stand today clearly incline toward a long rather than a short time.[2]

TRANSPORTATION AND DEPOSITION OF ENGLACIAL DRIFT.

If we turn to the best available evidence bearing on the manner and rate of drift transportation by the ice-sheet we meet with facts tending to the same general conclusion, viz., that the building of the moraines was a very slow process. The rate of glacial motion is necessarily a function of the rate of drift deposition. If it is sufficiently clear that the ice motion was very slow we have that much gained towards a determination of the probable rate of moraine building. The other function is the drift load, and we have now to consider what evidence can be brought to bear upon it and also what theoretical considerations indicate as the probable truth.

Here again the Greenland ice-sheet is the closest available analogue and the significance of its indications relating to drift load and deposition are well set forth by Professor Chamberlin. On these points he writes as follows:

> That considerable débris is borne in the basal portion of the ice is not questioned; indeed, the term, "englacial drift" was proposed by the present writer in recognition of its importance. Our best evidence of the amount

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[1] "View of the Ice age as two Epochs, the Glacial and Champlain." Proc. A. A. A. S., Vol. XLIV, 1895, p. 144. Also Am. Geol., XVI, August 1895, p. 107. For duration of Lake Agassiz see also "Glacial Lake Agassiz," by WARREN UPHAM. Monograph, pp. 241–242.

[2] In studying the history of such a glacier as the Muir of Alaska with its relatively rapid advances and retreats ("Glacier Bay and its Glaciers," by H. F. REID, 16th Ann. Rept. U. S. Geol. Survey; map opposite page 454), and like many of those that calve icebergs in Greenland, it must be remembered that the conditions of their motion are not at all like those of an ice-sheet and that they do not furnish safe criteria for interpreting ice-sheet motion.

and distribution of this is derived from the continental glacier of Greenland. It is there observed that débris prevails in the lower 50 or 75 feet of the ice-sheet, and occasionally reaches up to 100, or perhaps even 150 feet. The amount of this débris, if it were let down directly upon the glacier's bottom by melting in situ without concentration by the forward motion of the ice, would be measured by a very few feet, or by a fraction of a foot. The forward motion of the ice concentrates this at its edge, so that it may there reach, theoretically, any dimension, entirely without regard to its amount in any given vertical section of the ice. The thickness of the deposit formed from the englacial drift is quite as much dependent upon the length of time during which the edge of the ice remains at one line as upon the amount of drift which the ice may carry in any given vertical section. No safe inferences from the thickness of deposits of englacial drift can therefore be drawn with reference to the amount of englacial material present in any given portion of the glacier. If the ice were absolutely stagnant the deposit of englacial drift would be precisely that which was held in the ice above the point of deposit. If there was any forward motion of the ice while it was being melted away, there would necessarily be a concentration. If there be one foot of englacial débris in a given section and the ice moves forward 40 feet while the external heat causes a retreat of 1 foot, the englacial deposit should be 40 feet deep. The thickness of the englacial drift may therefore be quite as much an expression of prolonged time as of a large content of débris within the ice.

Referring to the manner in which the englacial débris becomes at length exposed and deposited Professor Chamberlin, continuing on the next page, says:

Instead of rising toward the surface of the glacier, it is believed, on the basis of observations in Greenland, to pursue a course nearly parallel to the base, on the whole, and to come out at the extremity of the glacier. To some slight extent it may become superglacial by ablation, but only to a limited degree.[1]

Again, describing more specifically the phenomena in Greenland, Professor Chamberlin says:

The débris belts are essentially parallel to the base of the glacier. They are chiefly confined to the lower 50 or 75 feet; sometimes they prevail up to 100 feet and rarely beyond. I think 150 feet might be named as a rather extreme limit. They are more abundant at the sides of the lobes than at the center, a fact that is significant in indicating the introduction of a notable part of the débris after the lobes were formed. In consonance with this the débris appears to be most abundant in the glacier-lobes which descend as cataracts or crowd between closely hugging cliffs. If, standing in front of a glacial lobe, the dirt bands are traced, many will be found disappearing at the cataracts, or the embossments of the bottom, or at the spurs on the sides.[1]

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[1] "Glacial Lake Agassiz," Monograph, pp. 249 and 250.

The general impression produced by such conclusions as these is that an ice-sheet probably carries somewhat less englacial drift than the tongues that, like those of Greenland so far described, branch off from the main sheet and descend several miles and 2000 or 3000 feet down ravines or constricted valleys. The tongues certainly have better opportunities to gather débris than the bottom layers of the main cap. And the force of this impression is greatly increased when we think of an ice-cap that deployed over so smooth a plain as did, for the most part, the Laurentide glacier in the area here considered.

Mr. Upham inclines to the opinion that "englacial drift was carried up through the lower quarter or third part of the ice-sheet, where, as in Manitoba, it was probably a mile thick."[2] But, as Professor Chamberlin has said, there seems to be no reason to suppose that the thickness of the bottom débris-laden layers bears a fixed ratio to the total thickness of the ice. Indeed, from the very fact that the upper part of a glacier moves forward faster than its lower layers, it follows that the bottom layers cannot rise beyond a very limited extent, except by overthrust in consequence of flow over high points or embossments that project upward into the ice. In passing over high obstructions high englacial drift may be introduced. But the amount of such drift appears to be really insignificant, and it even then becomes superglacial only after it has moved with the ice far enough forward into the peripheral zone of ablation to have had all the ice that overlies it melted off, or until it reaches the very edge and is thrust upward over a moraine or other obstruction.

Those who have not seen glaciers have often been much deceived as to the amount of englacial drift by the highly deceptive appearance of pictures of débris-laden, melting ice-tongues. Chamberlin and Salisbury both draw attention repeatedly to the effect of the spreading of fine dirt so as to blacken the whole ice wall. When small streams of clear water wash this away, or the dark surface has been removed with a pick, comparatively clear ice is seen beneath, and yet some of these layers or thin laminæ which they contain, may be the very ones that were supplying the blackening material. Large masses of englacial drift are rare and their forward motion is extremely slow, certainly much slower than that of the clean ice above, except where they occur, still more rarely, as lenses relatively high up in the glacier so as to have a considerable thickness of clear ice beneath them. In short, it seems to be shown that englacial drift is a far less voluminous constituent of ice-sheets than has been supposed by many. It keeps its importance, however, as almost the only means of drift transportation by continental glaciers like that which invaded the United States. But except under peculiar circumstances the amount in any given section of ice is almost insignificant. When all the circumstances are taken into account it seems probable that the load of débris is as great or greater in the Greenland tongues than it was in the Laurentide lobes in Ohio and Michigan. The coast of Greenland is mountainous. The ice flows out among many nunataks and along the base of high cliffs, and no doubt overrides many knobs and peaks and precipices from all of which it gathers material in such a way as favors its becoming superglacial or englacial. Then, too, the exceedingly rough country is favorable to the production of high overthrusts by which the bottom layers with their débris may assume relatively elevated positions in the ice.

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[1] "Recent Glacial Studies in Greenland," Bull. G. S. A., Vol. VI, 1895, page 205. Contrast with these ideas the opinion of MR. UPHAM, where he says, speaking of the great Leaf Hills moraine in Minnesota, that "perhaps not more than fifty or even twenty-five years [were occupied] for amassing these morainic hills 100 to 350 feet high on a belt 3 to 5 miles wide ! " ("Glacial Lake Agassiz," Mon., p. 242).

[2] "Sublacustrine Till," W. UPHAM, Am. Geol., Vol. XVII, June 1896, pp. 374–375.

When the ice-front was in Ohio or Michigan there was no chance for the formation of lateral moraines from cliff-fallings, nor of medial moraines from the detritus of nunataks. At that stage of glaciation the field of ice stretched away to the north-northeast without a break, and no land was exposed back of the edge. In Canada some of the path of the ice was rather rough, but not in any sense comparable in this respect with most of the coast of Greenland, and it was all deeply overridden at the time the ice reached across Lake Huron to points farther south. It follows that substantially all the northern drift of Michigan, Ohio, Indiana and Illinois was carried forward from Canada englacially. But the larger portion of the drift south of the lakes is of local origin, derived from rocks near by. This region, as the last ice-sheet found it, was probably a comparatively smooth drift plain, made so by earlier Pleistocene ice-sheets Almost the only way that local débris could become englacial was by being taken up, absorbed or incorporated directly into the lower layers of the ice as the glacier moved along. Under the great pressure of ice, hundreds or perhaps thousands of feet deep, this process must have become more or less effective. It seems almost certain that substantially all the drift south of the lakes was transported englacially, and in only the lower layers of the ice-sheet. The maximum load which can be carried in the bottom layers of the ice without overthrust cannot exceed a certain amount for a given pressure and rate of glacial flow, and that amount is probably not large. When the bottom layers become overloaded they clog beneath the ice and cease to move, while the cleaner upper ice forms a plane of shear above the clogged layers and overrides them. Professor Salisbury, writing of the glaciers of Greenland, says:

> Professor Russell has called attention to the fact that the movement of ice is influenced by the amount of débris which it carries. This doctrine finds abundant confirmation in the north. The lower part of the ice, which is well charged with débris, or altogether full of it, seems to virtually lose its motion and to become the bed over which the upper ice passes. It is not possible to say that its motion is absolutely lost, but many phenomena seem to make it certain that the upper portion of the ice of a glacier passes over the lower débris-charged portion in the same way that it passes over a rock bed. The lower part of the ice in such cases becomes virtually an ice conglomerate, the mobility of which is certainly slight.[1]

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[1] "Salient Points Concerning the Glacial Geology of North Greenland," by R D. SALISBURY. JOUR. GEOL., Vol. IV, No. 7, pp. 800–801.

It appears to be a plain inference, even in the case of the extremely slow motion of the Greenland cap, that however slowly the upper layers of the ice move, the débris-laden bottom layers move still more slowly. Even in a fiord tongue which moves 50 or 100 feet a day, if the ice is 1000 to 1500 feet or more deep the extreme bottom layers may move quite slowly.

The principles involved in basal clogging have been well brought out by Professor I. C. Russell. He reduces them to this proposition: "The rate of flow of glacial ice, under given conditions, will depend upon the percentage of débris commingled with it, and be least where the percentage is greatest."[1] For our present purpose this law may be advantageously restated in terms of drift transportation and deposition rather than ice-motion, thus: Whether the basal layers of a glacier will absorb or deposit débris at a given place or pass over without doing either, depends on their carrying an underload, an overload, or just an even full load at the existing velocity and pressure.

Under deep ice, however, the building up of ridges or prominences like terminal moraines, by the clogging of débris-laden bottom layers, would seem to be impossible, because the tendency there is to wear down and abrade every prominence of the land that is overridden. Clogging under deep ice probably occurs to some extent, but only by the shearing off of thin bottom layers which do not remain as subglacial prominences. Hollows of the land surface would tend to be filled up by clogging, and a mass of débris once dropped in such a place would tend to stay there unless the peculiar and rare conditions which lead the ice to scoop out basins came into play. While the general truth of Professor Russell's proposition is plain, and the principle stated is one of great value, it may be doubted whether it can have such a function as he supposes when he suggests that it was the determining cause of the moraines of recession and their peculiar distribution.[2]

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[1] "The Influence of Débris on the Flow of Glaciers." JOUR. GEOL., Vol. III, No. 7, pp. 823–832.

[2] In a footnote to his article (page 831) Professor Russell makes the following

The great Malaspina glacier of Alaska, so well described by Professor Russell, belongs to the Piedmont type, and is probably

suggestion: "That a series of terminal moraines in a formerly glaciated valley, or a similar succession of ridges left by a continental glacier, are not necessarily evidence of repeated climatic oscillations, but may have been formed during a uniform and continuous meteorological change favorable to glacial recession. That is, a débris-charged glacier may retreat for a time, then halt and again retreat, owing to its terminus becoming congested with foreign material, in response to a climatic change which would cause a glacier composed of clear ice to recede continuously and without halts."

It is hard to see how clogging of the lower layers could have the effect of building a ridge like a terminal moraine anywhere except at or very near the edge of the ice-sheet; and it seems certain also that the building of a great moraine must have required a relatively long duration of time — much longer than the building of the flat intermorainic plains of till. But under a uniform change of climate, as supposed by Professor Russell, it seems impossible to allow much more time for the building of a moraine than would be taken by a clear-ice glacier to retreat over an interval equal to the width of the moraine unless the formation of the moraine is supposed to begin under deep ice far back — at least several miles back — from the edge of the lobe. When the front of the Maumee ice lobe was at Fort Wayne the ice was probably 400 or 500 feet thick within a mile or two back from the edge, and its thickness increased to the northeast. From Fort Wayne to Port Huron there are five moraines in series with four intervals of about fifty miles each, and with wide till plains intervening. When the ice-front was just east of the Fort Wayne moraine, did basal clogging begin then at Defiance, forty-five miles back under the deep ice, or did the ice-front retreat from Fort Wayne to Defiance without clogging only to begin it again at the latter place? If the former, then we must set aside the law of heavy abrasion on subglacial prominences under deep ice. If the latter, then, as already pointed out, the time allotted for the building of the moraine is little if any longer than that which would be taken by a clear-ice glacier to retreat over a distance equal to the width of the moraine.

The Port Huron-Saginaw moraine is clearly traceable as a distinct individual from the highlands south of Georgian Bay, where it is about 1000 feet above the lake, descending to lake level at Port Huron, rising thence 300 feet to Ubly on the "thumb" of Michigan, descending again to lake level at Saginaw, rising again towards the northeast to the Au Sable River, and thence northwest nearly as far as Petoskey, where it is again about 1000 feet above the lake — a distance of over 400 miles. It seems hard to account for such a moraine by clogging alone, and for a series of them, the existence of which is a matter of simple inference from the facts now at hand, the difficulty becomes much greater. Speaking of the terminal moraines of the United States, Professor Chamberlin says: "Some of these have been traced several hundred miles in individual distinctness, and, by fair correlation, may be assumed to have been identified for a thousand miles or more." (GEIKIE'S "Great Ice Age," 1894. p. 740.)

But even if basal clogging in itself could produce moraines, that process taken alone could hardly be the cause of such a marked and widespread periodicity in the phenomena. The continuity and great length of individual moraines shows that the periodic rhythm of the oscillations affected wide areas; indeed, there lacks but little to the best modern example of it.[1] But this glacier is the dumping ground of hundreds of Alpine glaciers of the most pronounced type, all descending steep, short slopes from high mountains, and carrying heavy loads of débris—superglacial loads as medial and marginal moraines, as well as heavy englacial loads in their bottom layers. Contrasted with this the Laurentide glacier had no Alpine feeders whatever. Substantially all that it accomplished in the transportation and deposition of drift was done by its bottom layers in englacial fashion. The Malaspina apparently suggests nothing that would controvert the general conclusions drawn from other sources. For its most characteristic features are exceptional, and obviously do not apply to the Laurentide ice-sheet nor to ice-sheets in general.[2]

THE PROBABLE DURATION OF THE PERIODS OF GLACIAL OSCILLATION.

A little examination will show that no short period, such as 35, 100, or even 300 years will suffice for the building of the moraines. From Fort Wayne to Port Huron there are five moraines with four intervals of almost exactly fifty miles each. These constitute perhaps the simplest group in the whole moraine series. They have the widest and most regular intervals and some of them, when not too deeply water-laid, are the very best types of the structure characterizing deposition at a climax of readvance. The intervals are so wide, and the valleys in which

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prove that it was of continental extent. From present indications it would seem almost certain that future investigations will establish this as a fact. But even supposing moraines to be formed sometimes by basal clogging, what could be the cause of such widespread periodic clogging if not climate ?

[1] "Mt. St. Elias and its Glaciers," Am. Jour. Sci., Vol. XLIII, March 1892, pp. 169–182; "Malaspina Glacier," JOUR. GEOL., Vol. I, No. 3, pp. 219–245.

[2] Mr. Upham has recently enlarged and elaborated Professor Russell's suggestion, but apparently without throwing any new light on the obscure processes involved. (Am. Geol., Vol. XIX, June 1897.) He also endeavors to enforce the Malaspina glacier, which is a perfect example of the Piedmont type, as a criterion for interpreting the Laurentide ice-sheet or continental glacier. In this effort he even goes so far as to call the Malaspina glacier an ice-sheet—an application of the term which is clearly erroneous and misleading.

the broad Huron and later Erie-Huron ice-lobes advanced are so wide and smooth that the circumstances favoring simplicity were at a maximum.

Suppose it took the ice-front thirty-five years to retreat from the Fort Wayne to the Defiance moraine, receding at a uniform rate. That would be a little over twenty and a half feet a day. But this allows no time for retreat beyond Defiance, nor for the halt at the warm climax of retreat and the building of a moraine there of equal magnitude with that now seen at Defiance, nor for the readvance to Defiance, nor finally for the building of the Defiance moraine. If the Defiance moraine was built after a readvance and if the nature of the oscillation was such as shown in Fig. 1, then the time taken for the retreat from Fort Wayne to Defiance must have been only a fraction of the whole period of oscillation. We may measure the period of oscillation between the crests of the moraines, including always the destroyed moraine of the warm climax. We may assume further that the readvance is at least half of the previous retreat, and in this case the moraine of the warm climax next after the Fort Wayne moraine would be built at some point near Toledo and after it was finished the ice-front would readvance to Defiance. Then the first half of the period of oscillation would be measured between the crests of the Fort Wayne and Toledo moraines, and the second half between the crests of the Toledo and Defiance moraines. The two middle points of oscillation would then be half way between Fort Wayne and Toledo and half way between Toledo and Defiance. The first of these would be about at Defiance. On this basis the retreat from the crest of the Fort Wayne moraine to the middle point at Defiance would take one-fourth of the time of the whole oscillation and this includes half of the time of the building of the Fort Wayne moraine. On the basis of thirty-five years for the whole, this one-fourth part would occupy only about eight and three-fourths years, and surely half of this time would have to be taken to build half of the Fort Wayne moraine, and that would leave only four and three-eighths years for the ice-front to retreat fifty miles. The rate of retreat would then average about 164 feet a day. And further, this retreat would have to take place in the face of the continual advance of the ice, so that the ice would have to melt back probably considerably more than 164 feet a day. Such a conclusion is manifestly absurd and its absurdity is only increased when we reflect that this is the average per day for the whole year. During the winter months there must have been not only no great amount of melting, but more or less readvance because melting ceased; and it is probably true that for some months in the spring and fall the forces of advance and retreat were about at a balance. Only for three or four months in summer would the forces of retreat be effective, so that substantially the whole annual retreat would have to take place during the summer and the rate of retreat would have to be at least four or five times the daily average for the whole year, or 700 or 800 feet or more per day. It does not help the matter much to change the period to 100 or even 300 years. For it would still be necessary to postulate a high rate of retreat—seventy or eighty feet per day during the effective melting season. If the period were 3000 years the rate would still be seven or eight feet a day at that season. With the period at 6000 years the rate would be three and a half to four feet a day, and at 12,000 years one and three-fourths to two feet a day.

We may suppose, if we choose, that at every turn of retreat the ice-sheet became completely disintegrated and broken up, at least over a wide marginal belt, on account of the suddenness and intensity of the increased warmth. But such a supposition savors of catastrophism and does not seem to be in the line of probable truth. The equilibrium between glacial accumulation and ablation must have been a very delicate one. There could be no wide departure from a balance of forces without a corresponding great change in the extent of the ice-sheet. Surely the climatic conditions which permitted the ice-front to stand for a long time at Fort Wayne were not greatly different from those that permitted it to stand at Defiance or at Toledo. There is no need of supposing that sudden or violent climatic changes produced the oscillations. There is nothing in the phenomena of the drift that requires it, nor has anything been discovered in the behavior of the Greenland ice-sheet that suggests it. The summers were seasons of melting during the phase of advance as well as during that of retreat, and it may be doubted whether the most skillful observer could have detected any difference in the summers of the two phases unless he had made the most refined gauge measurements on the volume of the water discharged. Whether the ice-front would advance a little or recede a little or remain stationary during a long period of years was a matter of the utmost delicacy of adjustment. I doubt whether the average annual temperature for a period of years need differ more than two or three degrees to determine whether the ice-front shall stand at Fort Wayne or at Defiance.

Again, there seems every reason to suppose that the general advance of the ice-sheet was after the same manner as the retreat, only that the oscillations were reversed, and that it required the same duration of time. From the halt at Defiance the ice would retreat to Toledo, and then readvance to Fort Wayne, and so on. If this is a true assumption, then it would require us to suppose that the ice-sheet must be able to advance from Toledo to Fort Wayne in the same time, and hence at the same rate, as it is supposed to retreat over the same interval during the general recession. But it is manifestly impossible to suppose that the ice advanced at a rate of anything like 1000 or even 100 feet a day. The great wide lobe that advanced up the Maumee valley is not to be compared with the Muir, or the Karajak glacier, but rather with some part of the Greenland ice-cap that ends on land. It was not breaking off and floating away as bergs. It seems certain that its motion must have been very slow, probably not over two to five feet a day, even at the maximum.

But if it seems necessary to put the period of oscillation at 3000 years or more, it becomes a matter of comparatively small importance whether it be a little more or less. We have no means of knowing just what it was, but if 3000 years seems to be an extreme minimum and 6000 years seems better, there is no possibility of drawing the line just there and saying that it could not have been 10,000 years or even more. At the present day the combined weight of the facts, theories and analogies available to us seems to me to lean toward the conclusion that an oscillation period of between 5000 and 10,000 years would be the most satisfactory. If we take the Fort Wayne moraine to be five miles wide and the period of oscillation to be 5000 years, and if we suppose the period to be divided in two halves equal in time, one of advance to Fort Wayne over a space of fifty miles and the other of retreat from Fort Wayne over a space of 100 miles, then we may say in round numbers that it took 700 or 800 years to build the Fort Wayne moraine. If we take the period of oscillation to be 10,000 years, then it took twice as long.

THE SUPERPOSITION OF THE OSCILLATIONS UPON A GREATER AND MUCH SLOWER CLIMATIC VARIATION.

That there was a periodic oscillation of the ice-front of some kind or other needs no better proof than the simple fact of the existence of the moraine series itself. We have seen that by its influence upon climate precession would tend to produce a to and fro oscillation of the ice-front. We have seen also that there is a considerable amount of reliable evidence showing that the oscillations which took place did, in fact, have the character ascribed to precession. But if terrestrial climate had suffered no change from any other cause than that which produced the oscillations, then the ice-front would have gone on playing back and forth for an indefinite time over the same narrow strip of ground. But the moraines are distributed in a great series from south to north with intervals between them that are remarkable for their regularity, when due allowance is made for the influence of topography. This arrangement seems to be explicable only on the supposition that besides the oscillations there was another greater, slower change of climate in progress — many times longer in duration than the period of oscillation. Whatever their cause, the oscillations were obviously superposed upon this greater, slower climatic change. After the grand climax of advance, when the ice of this epoch reached its farthest point south, the long retreat began and the oscillations that made the moraines of recession went on round after round during the slow progress or the greater change. This is a truth that stands out clearly on the face of the larger facts and is entirely independent of all theories as to the cause of the oscillations or of the greater change itself. Here again the moraines of recession, by their arrangement, and by the regularity of their intervals, help us to a partial insight into the nature of this greater change—the real cause of the Ice age. Not that they show us the whole cause fully and clearly, for they do not. But they show us enough of its real nature to enable us to eliminate several hypotheses that have been suggested, and so to narrow the range of discussion. The cause of the greater change must have been of an astronomical nature, and there is apparently no alternative.

In order to see the full import of the facts we must see just how the oscillation is related to the greater change. If the oscillations were regular (either with equal time intervals, or with time intervals that varied progressively at a uniform rate) and the greater change also regular (uniform or varying at a uniform rate) then the moraine series would tend to be regular, but if either one or both of the changes were irregular, then the moraine series would be irregular. To get a regular moraine series out of a combination in which either factor was irregular would be accidental, and an assumption that such a cause has produced the moraine series would be gratuitous and without reasonable foundation.

A careful analysis of the effect of topography in causing irregularities in the moraine series seems to show that the intermorainic intervals are not uniform, but increase from south to north. By reference to the map it will be seen that from the first moraine back to the ninth, or Fort Wayne moraine, the intervals are shorter than from Fort Wayne northward. The effect of topography can be best understood by considering the glacier in its advancing phase.

When the ice-front was at the Hagenville (15th) and Alcona (14th) moraines, the apex of its lobe in the Huron basin was in the present lake bed, and so cannot now be exactly located nor measured. But at the next halt the ice-front stood at the Port Huron-Saginaw moraine (13th). This is the first one now fully recorded on land. At that halt the ice was held back by the highlands south of Georgian Bay in Ontario, and by those southeast of Petoskey in Michigan, and it was also held back about fifty miles by the "thumb" of Michigan. With further advances the separated Saginaw and Huron lobes moved forward nearly equally at first, but soon the Saginaw lobe met higher ground, and slowed its pace, while the Huron lobe moved on more rapidly and met and blended with the Erie lobe coming up the Erie basin from the northeast, and the two advanced as one lobe up the Maumee valley. The ice clogged more and more against the high ground in southeastern Michigan, and began the building of a great interlobate moraine upon it. This obstructed the advance of the Maumee lobe pretty effectually on the northwest side, while the high ground along the south side of the Erie basin did not allow of much expansion on that side either. Hence the advance was mainly up the wide flat Maumee valley until Fort Wayne was reached. At this point there came an important change. The ice-front had almost reached the flat rim of the Erie basin along that part of the front line which extends from Fort Wayne eastward about 140 miles, nearly to Mansfield, Ohio—to the east side of the head of the Sciota valley. The subsequent advances found ample room for expansion in the most advantageous way; that is, in a southerly direction and down grade. The ice soon began advancing down the Wabash and White River valleys in Indiana, and down the Miami and Sciota valleys in Ohio. Besides, the Maumee lobe had now pushed so far ahead of the Saginaw that the obstruction on its northwest side in Indiana had been somewhat relieved. But before becoming distinctly segregated into four sub-lobes, the ice advanced for a few steps very evenly over the level summit plateau, forming the remarkably regular and concentric series of moraines south of Fort Wayne and extending over into Ohio. At the sixth and fifth moraines the ice-front began to push slightly forward down the Miami valley, but the lobe did not become distinct until the fourth moraine. From that to the first moraine the Miami lobe developed more and more individuality. The first four moraines mark the fully developed lobe and the circumstances under which they were made probably accounts for the smallness of two of their intervals—eight and twelve miles between the second and third and the third and fourth respectively. The Miami was the smallest and narrowest of the four valleys and hence its ice-lobe was more cramped than the others. Besides, there was no such concentration of advance in the Miami valley as there had been before in the Maumee. The pressure was relieved by the other three lobes, while from Detroit and Cleveland to Fort Wayne the large Erie-Huron lobe was cramped by highlands on its sides and hence pushed forward in a comparatively long, sharp point.

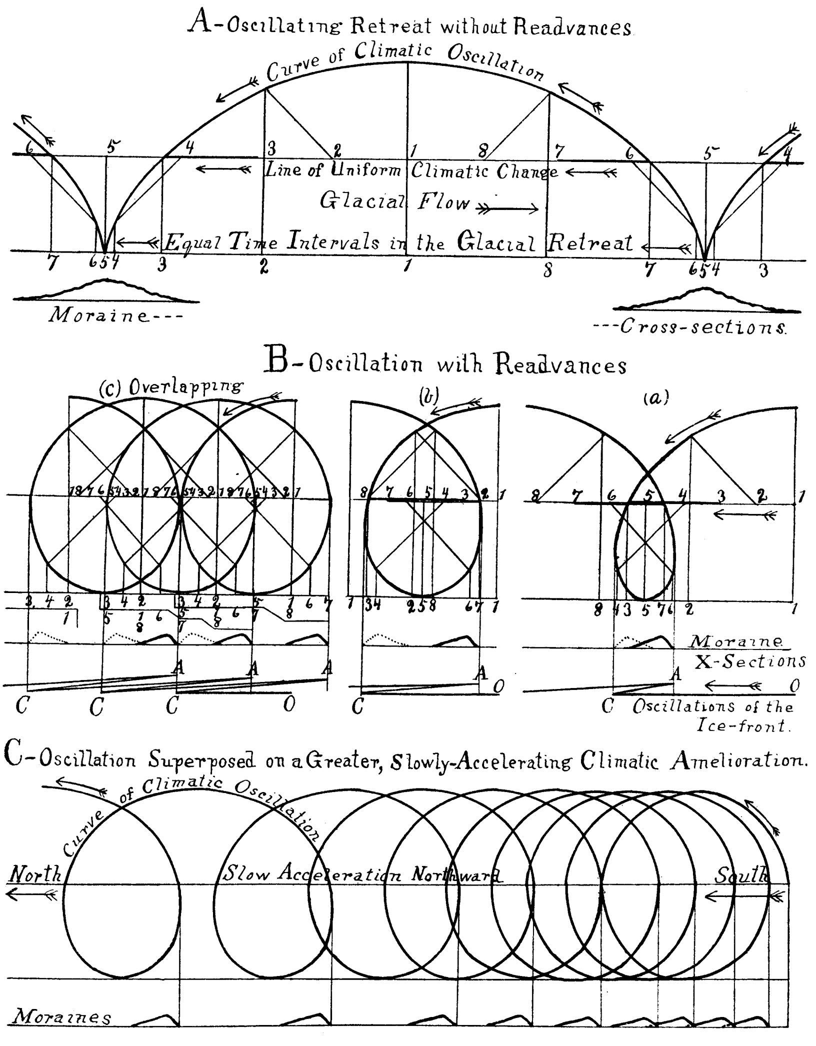
In this discussion of the intervals we have followed the ice in its advancing phase. We have only to reverse the order of events to see that the influence of topography was substantially the same during the retreat.

This, as it seems to me, is the true explanation of the variations of the intermorainic interval, and it indicates that the narrow intervals which prevail from the first to the ninth moraines are not out of harmony with the wider intervals from the ninth to the thirteenth. The shorter intervals of these moraines do not indicate, as might be supposed, a radical difference in climatic conditions, nor of amplitude of oscillation, nor, possibly, of the rate of the general retreat, but mainly the influence of topography.

If the moraines showed nothing further it would seem clear that the rate of the main retreat had been perfectly uniform, or at least very nearly so. But if we turn to northern Michigan and compare the intervals of four moraines there with the four south of Fort Wayne, an increase of the interval northward seems to be suggested. South and southwest of Fort Wayne four parallel moraines (the sixth to the ninth) lie within a space of forty-five miles. They were formed at the broad apex of the Maumee lobe expanding on a nearly level plain. In the north there are four parallel moraines (the twelfth to the fifteenth) also in a space of forty-five miles on a line running southwest from Rogers City past Gaylord. These moraines are banked up against the northeast face of the highlands and mark a great reëntrant angle of the ice-front. The fifteenth is 800 or 900 feet lower than the twelfth, while the ninth near Fort Wayne (on a line running southwest from Paulding, Ohio) is only about 100 feet below the sixth. At present we have no measure of the intervals in the north except on this steep slope. It seems plain, however, that if these four moraines had been laid down on a level plain without being banked up against the highlands the normal interval would have been considerably greater than it is. On the other hand, near Fort Wayne it seems clear that if the highlands of northeastern Ohio and western Pennsylvania and New York had been absent and a level plain there instead, so that the expansion could have been distributed evenly along the edge, the normal interval would have been somewhat less than it is.

These facts seem to show that while the oscillations were going on, probably at a substantially regular rate, the main climatic amelioration and its resulting glacial retreat was also going on, not uniformly, but at a progressively increasing rate. From the first (or second) moraine near Cincinnati, where the great advance of this epoch had stopped and the great retreat begun, the ice-front retreated at first very slowly, but faster and faster as the front receded northward. Here again the character of the simple harmonic motion seems to be revealed as the probable manner of the varying rate of retreat. And this gives a decidedly astronomical quality to the cause. Whether the cause was due to some greater variation like precession, or to some slow orbital change, either of eccentricity or of magnitude affecting the distance of the earth from the sun independently of eccentricity, it may at least be said that any variation of climate that can be so represented must spring from a cause which proceeds in a great curve, and if glacial epochs are periodic, as they may be, then the variation is expressed by a closed curve, either circular or elliptical.

The manner of retreat under such a combination of forces may be represented graphically with approximate accuracy as follows: Assuming the oscillation to be superposed upon a greater amelioration having a uniform rate, the resulting path would be an epicyclic curve. If the recession took the form of retreats and halts without readvances the curve would come to a point at the moraines as in Fig. 4, A, and the moraines would have cross sections, under the simplest conditions of formation, like that shown in the figure. With readvances the curve would be a looping epicycle as in Fig. 4, B, (*a*) and (*b*), and if the readvances covered more than half of each preceding space of retreat the loops would overlap as in Fig. 4, B, (*c*). In both free and overlapping loops, the forms of the moraines would be as shown in Fig. 1 at A, and in Fig. 4, B, and C. As we have seen, this last appears to have been the actual manner of retreat, at least in Ohio, Indiana, and Michigan. This is shown in Fig. 4, B, (*c*). If the greater climatic variation is truly represented by a simple harmonic motion, then the overlapping of the loops was most extensive near Cincinnati, and decreased going northward. This order of retreat is represented approximately by Fig. 4, C. The facts seem to favor this method of interpretation quite strongly, but it is not necessary to pursue the theoretical aspect of the problem further here. It is suggested in this paper that precession of the equinoxes may have been the cause of the secondary climatic oscillations which produced the moraines of recession. But no statement, nor even a definite opinion, is ventured as to the cause of the greater, primary variation of climate which brought on the Ice age itself, except that it was of an astronomical nature. It may be added, however, that the astronomical theory of Croll even as modified and reënforced by Ball, is thought not to afford an adequate or satisfactory explanation. As to those other various hypotheses which postulate purely terrestrial causes, such as the displacement of the



A-Oscillating Retreat without Readvances

B-Oscillation with Readvances

C-Oscillation Superposed on a Greater, Slowly-Accelerating Climatic Amelioration.

Curve of Climatic Oscillation
Line of Uniform Climatic Change
Glacial Flow
Equal Time Intervals in the Glacial Retreat
Moraine---
---Cross-sections.
(c) Overlapping
(b)
(a)
Moraine X-Sections
Oscillations of the Ice-front.
C
A
O
Curve of Climatic Oscillation
North
Slow Acceleration Northward
South
Moraines

FIG. 4. Showing combinations of the period oscillation with the greater climatic change.

Gulf Stream by the submergence of the Isthmus of Panama or by the elevation of a supposed Antillean continent, or those that rely upon mere epeirogenic uplift in the north, they have no sort of intelligible relation to the characters revealed by the drift. In fact they appear to fall so far short of explaining these characters that there seems to be no longer a hope of gaining any real advantage from their consideration.

SUMMARY.

1. Between Cincinnati and Mackinac the Wisconsin drift formation has fifteen terminal moraines which form a consecutive series marking the retreat of the last ice-sheet; and there are three more farther north probably belonging to the same set. The series seems to be complete and is believed to constitute the simplest and most perfect known.

2. Making due allowance for the influence of topography, it appears that the intervals between the members of the series are remarkably regular, suggesting periodic halts or oscillations of the retreating ice-front, which appear to be attributable only to a periodic change of climate. But, excepting the annual period and a thirty-five-year period deduced by Forel and others from glacial and meteorological observations, the only periodic change of climate known is that due to the precession of the equinoxes with a period averaging 21,000 years and a minimum of 10,500.

3. A study of the forms of the moraines where they were made under the simplest conditions shows that they were always made at the climax of a readvance. In one instance at least the readvance appears to have covered more than half of the space of the previous retreat. Theoretically, the influence of precession on climate would cause a to and fro oscillation of the ice-front after the manner of a simple harmonic, and this superposed upon a greater and slower change, would produce an oscillating retreat with minor periodic readvances. This appears in fact to have been the manner of retreat during the formation of the moraine series, for those formed under the simplest con-

ditions have their crests forward; they have relatively short, steep front slopes and long gentle back slopes.

4. In attempting to deduce a period of oscillation from the study of existing things, the present ice-cap of Greenland was taken as the closest analogue for interpreting the drift of the Laurentide ice-sheet, and the chief reliance is placed in the observations of Professors Chamberlin and Salisbury. From these the conclusion is reached that the frontal edges of the great ice lobes that made the moraines of recession moved only very slowly, so slowly as to be in substantial accord with a period of oscillation equal to the minimum value of the precessional period. A period of between 5000 and 10,000 years, however, would seem to accord most closely with the phenomena. From Fort Wayne to Port Huron there are five moraines with four intervals of about fifty miles each. On this basis the Fort Wayne moraine with a width of five miles would have required something between 700 and 1600 years for its making.

5. The regularity of the oscillation and also of the greater climatic change upon which it was superposed both point clearly to astronomical causes. The periodic oscillation may have been due to precession, but no opinion is ventured as to the cause of the greater change. On this basis then, it took the ice-front 75,000 to 150,000 years to retreat from Cincinnati to Mackinac, and the whole glacial epoch lasted at least 150,000 years and possibly 300,000 or more. And if glacial epochs are periodic, as they may possibly be, then this period is only a fraction of the great cycle of climatic change.

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